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RESEARCH MEMORANDUM

SOME DYNAMIC CHARACTERISTICS OF A TURBOJET ENGINE FOR LARGE ACCELERATIONS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Acceleration characteristics of an axial-flow turbojet engine with a fixed-area exhaust nozzle were obtained from transients induced by large steps in fuel flow under sea-level static conditions. In the low-speed range, initial increases in thrust were found to be negligible, regardless of the size of the fuel step, so that the rate of change of thrust was almost directly proportional to the rate of change of speed. Accelerations through surge were successful. For a given fuel flow, acceleration was a function of engine speed regardless of the size of the transient; above an optimum fuel flow at each speed, acceleration was limited. Maximum acceleration and thrust appeared obtainable through the use of a proposed fuel schedule that required only small initial steps in fuel flow.

The apparent linearity of the engine (constant response time) was found to extend over a range of transients up to 15 percent of rated speed.

INTRODUCTION

In research and development associated with control systems for gas-turbine engines, it has become virtually standard practice to obtain the engine dynamics as a prerequisite to both control synthesis and experimental evaluation of specific control systems. The dynamics of gas-turbine engines are currently obtained by several methods, among which are included the response of the engine to step inputs, the response to sinusoidal inputs, and harmonic analysis of the response to arbitrary inputs (reference 1). The engine dynamics thus obtained have indicated that, for limited excursions from equilibrium (approximately 5 percent of maximum engine speed), the gas-turbine engine approaches a first-order linear system (references 1 to 4). Assumption of a first-order linear engine facilitates analytical control synthesis. It is also useful for determination of the characteristics of any specific experimental control (providing the test program is limited to small transients) and results in resonably good correlation between analytical and experimental studies of controlled engine instability (reference 4).

Because small transients permit the assumption of a first-order linear engine, much of the investigation of gas-turbine dynamics has been restricted to limited accelerations and decelerations. However, a realistic concept of gas-turbine engine dynamics would be incomplete without knowledge of engine response during large, as well as small, transients. Engine response during large transients has practical significance inasmuch as large transients may occur during combat maneuvers and wave-off conditions. 2602

In order to determine gas-turbine engine dynamics during large transients, several series of accelerations were made on a turbojet engine under sea-level static conditions by means of large step inputs of fuel flow at the NACA Lewis laboratory. By making successively larger transients to the same final speed, it was possible to determine the effect of the transient size on engine response time; and by making successively larger transients starting from the same initial speed, it was possible to determine the maximum potential of the engine with reference to acceleration and rate of change of thrust. These data and the acceleration characteristics of the engine derived therefrom are presented and discussed in this report.

APPARATUS

Engine

The turbojet engine used in this investigation had an eleven-stage axial-flow compressor, a single-annulus combustion chamber, and a two-stage turbine with a fixed-area exhaust nozzle. The rated engine speed of this engine is 12,500 rpm. The fuel pump was separately driven by an electric motor rather than from the conventional accessory pad drive so that the fuel pressure would be independent of engine speed.

Control System

Desired speed settings and changes in engine speed were accomplished by suitable regulation of the fuel flow in an open loop system (no feedback of engine speed). A voltage scheduler with a switching mechanism to give step changes supplied a direct-current signal to a power amplifier that actuated a motor-operated fuel valve (fig. 1).

Instrumentation

Recorder. - All transient data were recorded on a multichannel recording oscillograph. The oscillograph elements had a sensitivity of 1-inch deflection per 0.43 millivolt and were damped to an effective time constant of approximately 0.005 second (time constant = time to reach 63 percent of final value, following a step input).

Engine speed. - Transients in engine speed were measured by recording the output of a small tachometer generator on the recording oscillograph. The high-frequency ripple from the generator was filtered out of the speed-measuring circuit with an RC (resistance-capacitance) circuit filter having a time constant of about 0.07 second.

Pressures. - Transients in compressor-discharge and fuel pressure were measured with a bridge-type strain-gage pickup energized by a 3000-cycle carrier system. The apparent time constant of the measuring circuit was 0.02 second.

Thrust. - A thrust link coupled to a strain-gage pickup was used for transient-thrust measurements. The engine mount and the thrust-link system were underdamped, but the data indicated thrust measurements with approximately the same response time as the pressure measurements.

Temperature. - Tail-pipe temperature was measured by six 24-gage chromel-constantan thermocouples connected in series and the output voltages were measured on the recording oscillograph. The thermocouples had time constants of approximately 0.5 second.

Test Procedure and Data

The experimental program consisted of large transients in speed over the operative speed range of a turbojet engine. Changes in speed were made by a step in fuel flow which varied slightly from its analytical form because of a lag in the fuel system (time constant $\approxeq$ 0.11 sec).

The first phase of experimental data consisted of accelerations from various initial speeds to the same steady-state final speed of 92 percent rated speed. Typical data of engine speed and fuel pressure recorded on the oscillograph are shown for several of the speed transients in figure 2.

Experimental data for successively larger speed changes from idle engine speed (taken as 38 percent rated speed) to various steady-state final engine speeds are shown on oscillograph traces of fuel flow, engine speed, compressor-discharge pressure, and thrust in figure 3.

The fuel flow is measured for these data (fig.3) from the pressure drop across the fuel nozzle, which accounts for the slight decrease in the fuel flow as compressor-discharge pressure increases. The transient temperature was recorded for only the smaller speed transients because the high initial temperatures associated with the larger fuel steps resulted in destruction of the thermocouples. Oscillations of the thrust trace were due to an underdamped engine mounting system. Therefore, mean values were used for plotting thrust values.

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RESULTS AND DISCUSSION

Linearity

For small steps in fuel flow, the engine response can be represented by the time required for the engine speed to reach 63 percent of its final value. For larger and larger transients, all ending at the same final speed (fig. 2), the 63-percent points will be the same in the linear range. A plot of these 63-percent points is shown in figure 4 as a function of the change of speed incurred during the successive accelerations. A linear range (constant response time) of approximately 15 percent rated engine speed is indicated in figure 4; for larger transients the response time increased rapidly.

If slopes are taken of the engine-speed traces in figures 2 and 3, curves of engine acceleration can be obtained for each of the engine transients initiated by the different steps in fuel flow. These acceleration data are plotted in figure 5 for the accelerations to the same final speed (fig. 2) and in figure 6 for the accelerations from idle to different final speeds (fig. 3). Examination of figures 5 and 6 indicates that the linear region of operation, as characterized by the straight-line variation between acceleration and engine speed, extends over a speed range of approximately 15 percent rated speed for transients initiated anywhere within the engine operating range.

The comparatively large region of engine linearity encompasses many of the transients that might be expected during combat maneuvers and from initiation of tail-pipe burning, and is therefore significant in that the engine response to such disturbances may be predicted from straightforward linear analysis.

Maximum Acceleration and Thrust

<u>Maximum acceleration</u>. - The acceleration data plotted in figure 6 for successively larger fuel-flow steps from idle speed indicate that the initial acceleration is insensitive to the amount of fuel flow added. For example, on figure 6 it can be seen that at 40 percent rated speed

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the values of acceleration all coincide despite the existence of different fuel flows at the same speed. The fact that no increase in acceleration was obtained from increasingly larger fuel steps implies that the physical limitations of the engine with respect to acceleration have been reached. This limited acceleration may be the result of poor combustion efficiencies incurred at the over-rich fuel-air ratios or the result of reduced turbine and compressor efficiencies attributable to the large deviations from equilibrium operation or both.

As shown in figure 6, an envelope of all the acceleration curves may be drawn that represents the line of maximum acceleration for the engine. Accelerations resulting from the largest fuel-flow steps do not coincide with this maximum acceleration envelope because violent surge in these transients resulted in a loss of acceleration (see compressor-discharge-pressure traces, figs. 3(d) and 3(e)). This successful acceleration through surge, accompanied by only small losses, is not necessarily characteristic of other turbojet engines.

The mean curve of figure 5 is shown in figure 6 in order to help fill out the contour of the maximum acceleration envelope. It is important to note, however, that figure 5 contributes evidence to support the assumption that the maximum acceleration line of figure 6 is unique (for this engine) and not dependent upon how the fuel flow was added or at which initial speed the transient was incurred. The four largest transients of figure 5 show that the same final value of fuel flow resulted in approximately the same values of acceleration, although the change in fuel flow and the initial speed were different in each case.

Maximum thrust. - From the data of figure 3, a curve of thrust against engine speed can be obtained for each of the fuel-flow steps, as shown in figure 7. These curves exhibit thrust characteristics similar to the acceleration characteristics. The initial jump in thrust is independent of the size of the fuel step, and the values of thrust during the largest transients are adversely affected by the existence of surge. The small increase in thrust for a step change in fuel flow from idle speed and also from any other speed in the low-speed range (equivalent to the spread in the thrust curves along a line of constant speed) indicates that, for sudden demands upon the engine at low speeds, appreciable increases in thrust can be realized quickly only as a result of rapid increases in the speed level of the engine.

The relation between thrust and acceleration can be obtained from a cross plot of figures 6 and 7, and is shown in figure 8 for lines of constant speed. From figure 8 it can be seen that maximum thrust corresponds very closely to maximum acceleration for a given speed. In general, the flatness of the constant-speed lines indicates that the possible increase in thrust resulting from a step in fuel flow at constant speed is relatively small compared with the available increase in acceleration. Engine acceleration along the contour of maximum acceleration would therefore result in approximately maximum thrust as well as maximum acceleration.

Fuel-Flow Schedule

The acceleration curves of figure 6 are lines of constant fuel flow, and the points of tangency with the maximum acceleration envelope therefore designate the minimum fuel flows associated with maximum acceleration for transients initiated from each equilibrium speed. If the fuel 2602
flow and speed for each point of tangency are plotted, a schedule of fuel flow for acceleration is thereby described that should result in maximum acceleration and thrust. This fuel-flow schedule for acceleration is shown in figure 9 together with the equilibrium operating line of the engine. A step in fuel flow from the equilibrium line to the fuel schedule line would result in maximum initial acceleration and thrust. Optimum conditions would then be maintained by permitting the fuel flow to increase with speed according to the fuel schedule until the desired value of speed is attained, at which point the fuel flow would be reduced by a step down to the equilibrium value. Inasmuch as the fuel schedule calls for only small initial steps in fuel flow, its use would result in a minimum temperature overshoot consistent with maximum acceleration and might conceivably reduce the possibility of surge and blowout.

The advantage of the fuel schedule with respect to time of response may be seen from figure 10, which compares the speed-time data of figure 3 with a hypothetical acceleration obtainable with the fuel schedule. Speed-time data for the fuel schedule were obtained by integration of the maximum acceleration envelope (fig. 6) such that

$$t - t_0 = \int_{N_0}^{N(t)} \frac{dN}{\dot{N}}$$

where

t	time, sec
t_0	time at start of transient
N_0	speed at start of transient, rpm
$N(t)$	speed at time t, rpm
N	speed, rpm
$\dot{N}$	acceleration dN/dt

The curve shown for acceleration with the fuel schedule assumes that the use of a smaller fuel step would eliminate surge so that the value of acceleration at any given time would correspond to a point on the maximum acceleration envelope.

SUMMARY OF RESULTS

Large fuel steps, resulting in transients over virtually the entire 2602 operating range, were utilized to provide information relative to the dynamics of an axial-flow turbojet engine with a fixed-area exhaust nozzle operating under sea-level static conditions. The results of this experimental investigation are summarized as follows:

1. The turbojet engine utilized for this investigation accelerated successfully through surge.

2. In the low-speed range, thrust was almost entirely a function of engine speed. For large transients initiated at low values of engine speed, the immediate increase in thrust resulting from a step in fuel flow was negligible, and rapid and appreciable changes in thrust were attainable only from rapid increases in engine speed.

3. From various-size fuel steps, all ending at the same fuel flow, a single relation between acceleration (or torque) and engine speed was obtained for a given final fuel flow, regardless of the size of the transient.

4. Acceleration resulting from a step in fuel flow was limited to a maximum value at each engine speed, regardless of further increases in the size of the fuel step above an optimum value. A curve indicating the maximum acceleration attainable at each engine speed was obtained from the envelope of acceleration-speed data for different-size fuel steps.

5. A fuel schedule was obtained from the data that would result in maximum acceleration and thrust with minimum fuel flow for any desired change in operating level. This fuel schedule required relatively small steps in fuel flow and is therefore considered advantageous because of lower initial temperatures and possible elimination of surge and blowout.

6. The engine appeared to be essentially linear for transients in speed up to 15 percent rated engine speed, in that a constant response time and a straight-line variation between acceleration and speed were obtained for this speed range.

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REFERENCES

1. Delio, Gene J.: Evaluation of Three Methods for Determining Dynamic Characteristics of a Turbojet Engine. NACA TN 2634, 1952.

2. Himmel, Seymour C., and Krebs, Richard P.: The Effect of Changes in Altitude on the Controlled Behavior of a Gas-Turbine Engine. Jour. Aero. Sci., vol. 18, no. 7, July 1951, pp. 433-441.

3. Taylor, Burt L., III, and Oppenheimer, Frank L.: Investigation of Frequency-Response Characteristics of Engine Speed for a Typical Turbine-Propeller Engine. NACA Rep. 1017, 1951. (Supersedes NACA TN 2184.) 2602

4. Dandois, Marcel, and Novik, David: Application of Linear Analysis to an Experimental Investigation of a Turbojet Engine with Proportional Speed Control. NACA TN 2642, 1952.

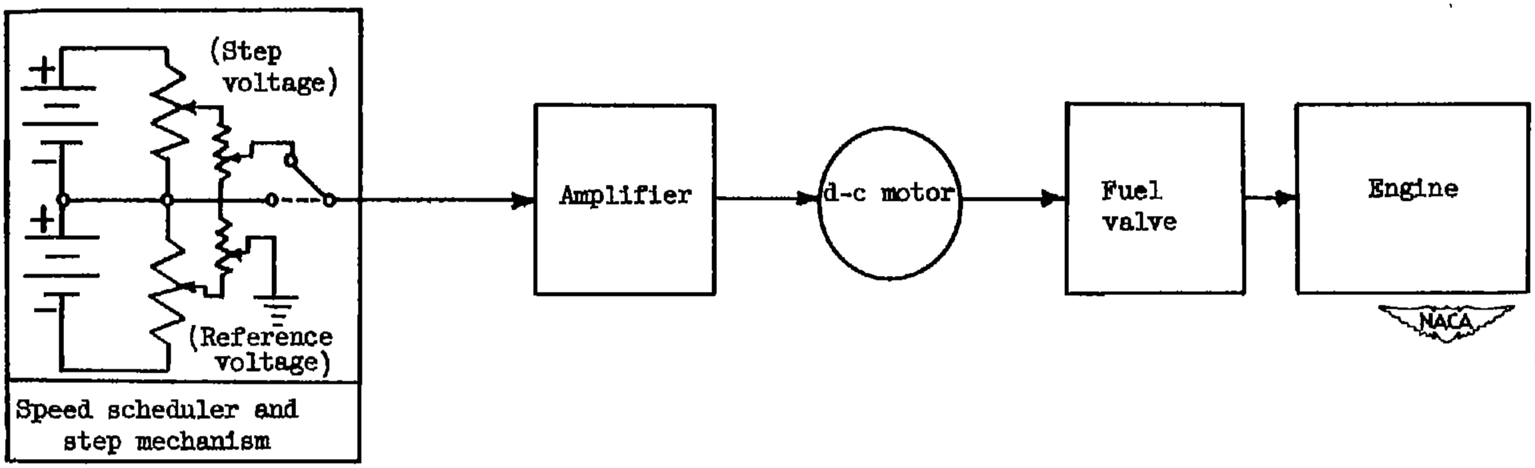

Figure 1. - Block diagram of control system.

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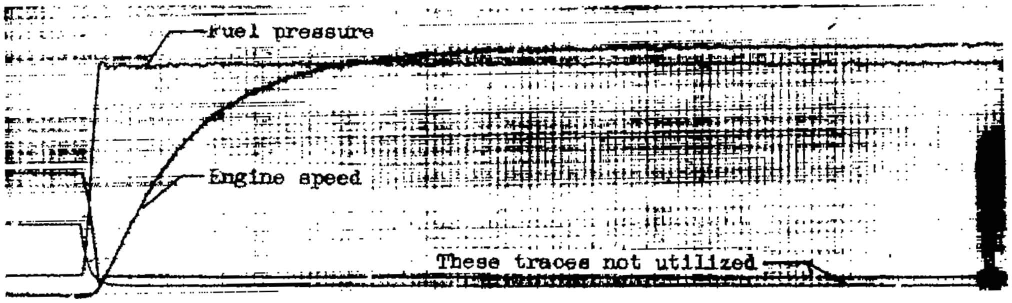
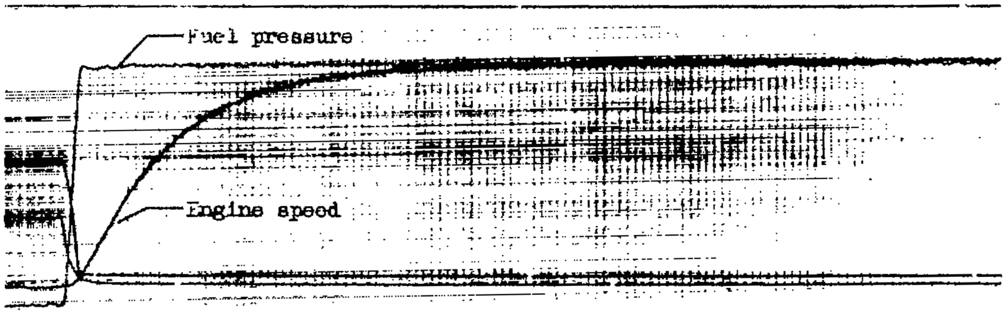
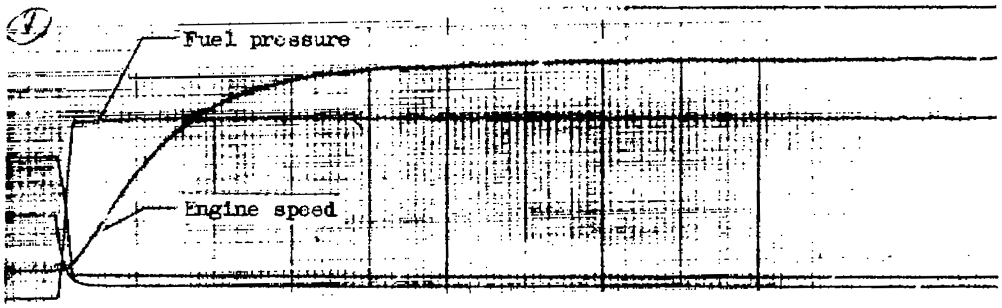


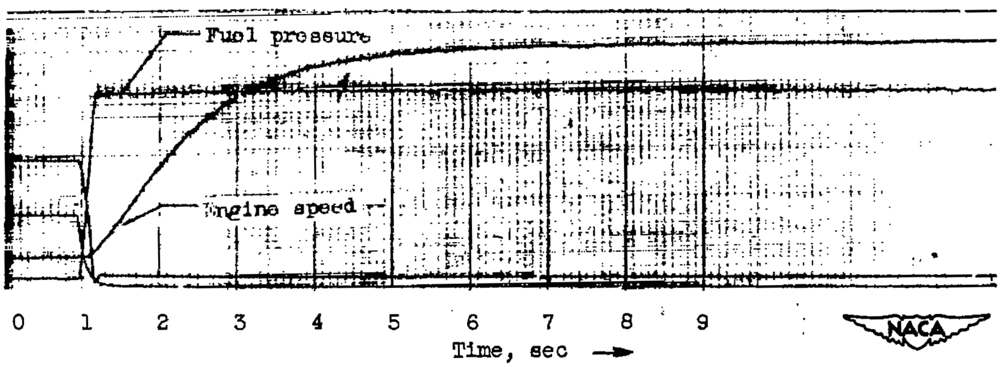
(a) Initial engine speed, 79 percent rated; change in engine speed, 13 percent rated.



(b) Initial engine speed, 76 percent rated; change in engine speed, 16 percent rated.



(c) Initial engine speed, 71 percent rated; change in engine speed, 21 percent rated.



(d) Initial engine speed, 68 percent rated; change in engine speed, 24 percent rated.

Figure 2. - Response of engine to step change in fuel flow from various initial engine speeds to 92 percent rated.

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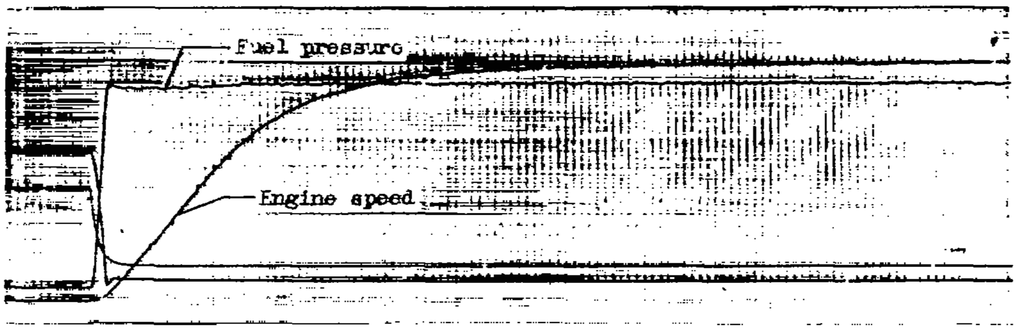
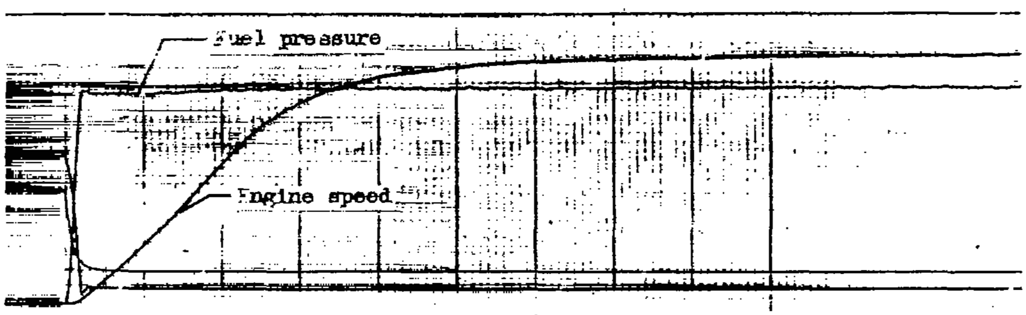
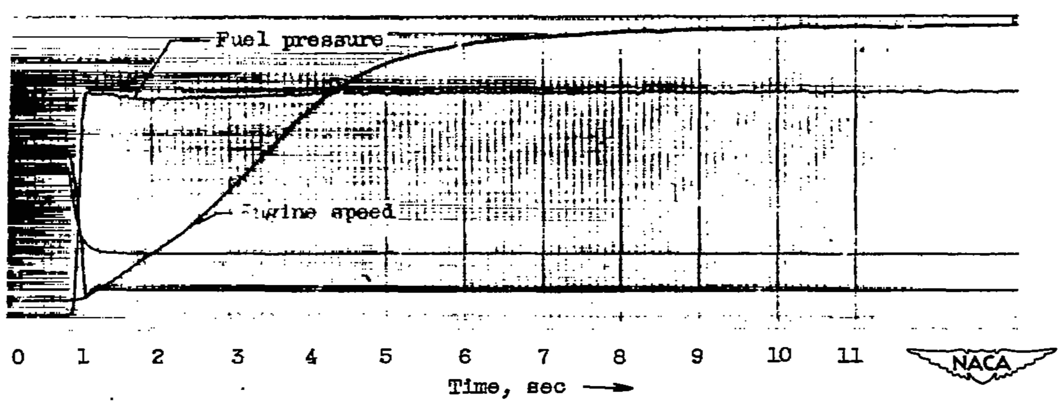


(e) Initial engine speed, 63 percent rated; change in engine speed, 29 percent rated.



(f) Initial engine speed, 58 percent rated; change in engine speed, 34 percent rated.



(g) Initial engine speed, 52 percent rated; change in engine speed, 40 percent rated.

Figure 2. - Concluded. Response of engine to step change in fuel flow from various initial engine speeds to 92 percent rated.

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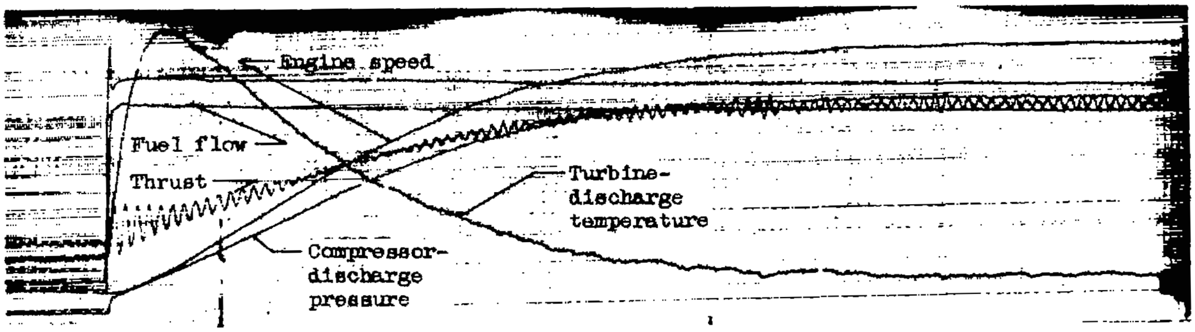
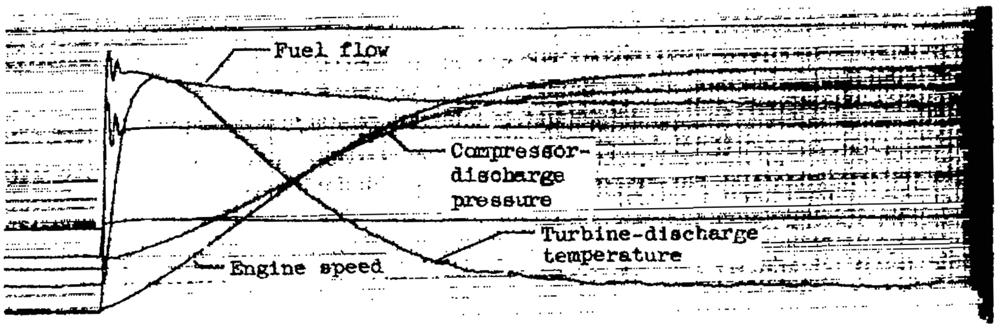
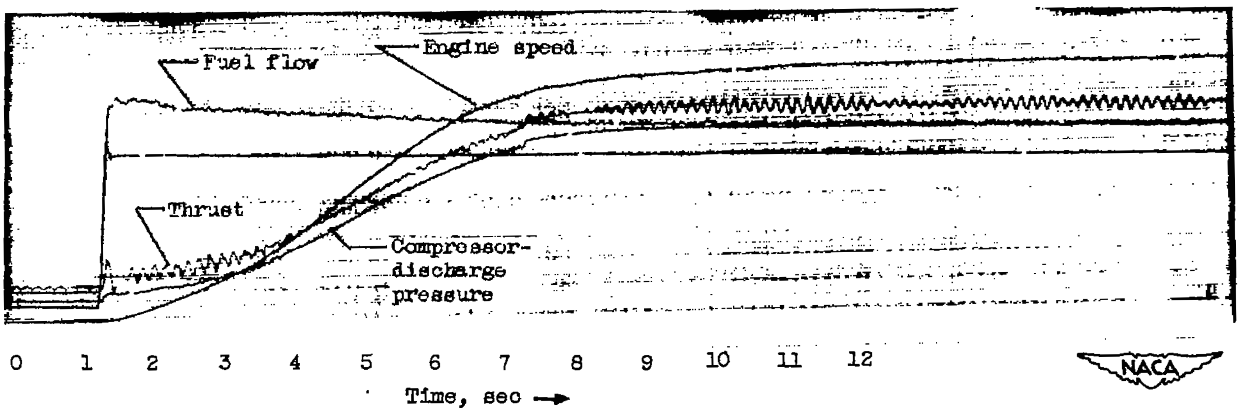


(a) Final engine speed, 66 percent rated; change in engine speed, 28 percent rated.

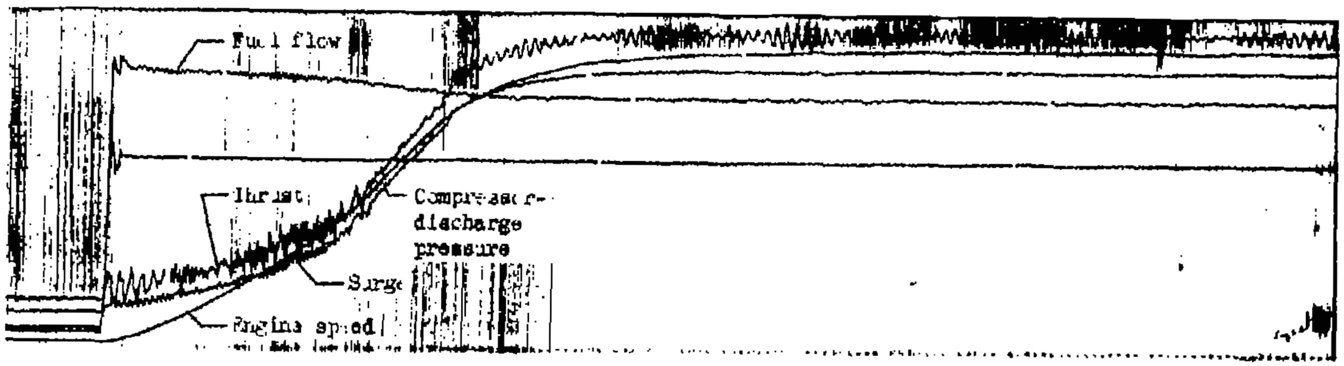


(b) Final engine speed, 74 percent rated; change in engine speed, 36 percent rated.

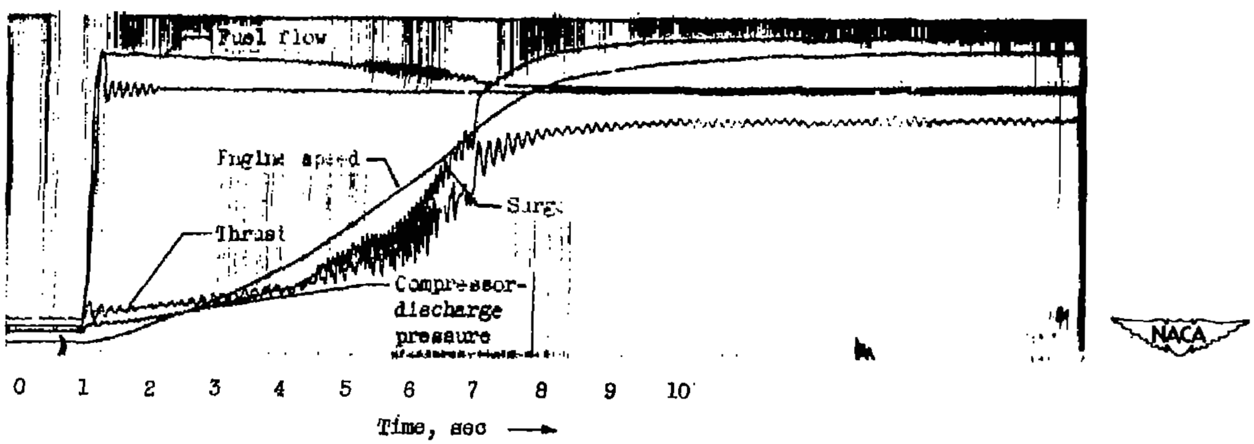


(c) Final engine speed, 81 percent rated; change in engine speed, 43 percent rated.

Figure 3. - Response of engine to step change in fuel flow from idle speed.



(d) Final engine speed, 89 percent rated; change in engine speed, 51 percent rated.



(e) Final engine speed, 95 percent rated; change in engine speed, 57 percent rated.

Figure 3. - Concluded. Response of engine to step change in fuel flow from idle speed.

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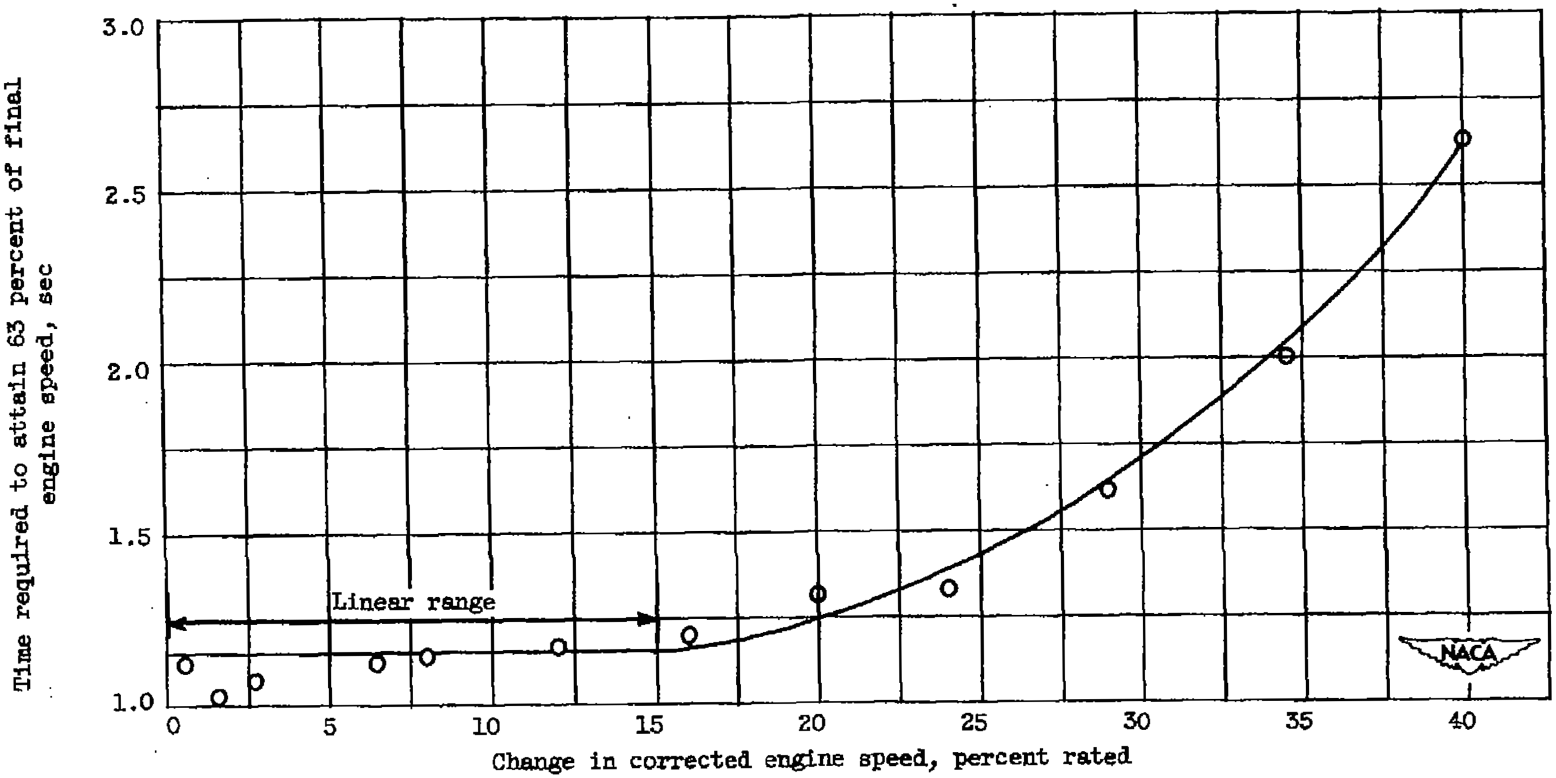

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Figure 4. - Variation of response time with size of speed change for transients ending at 92 percent rated speed.

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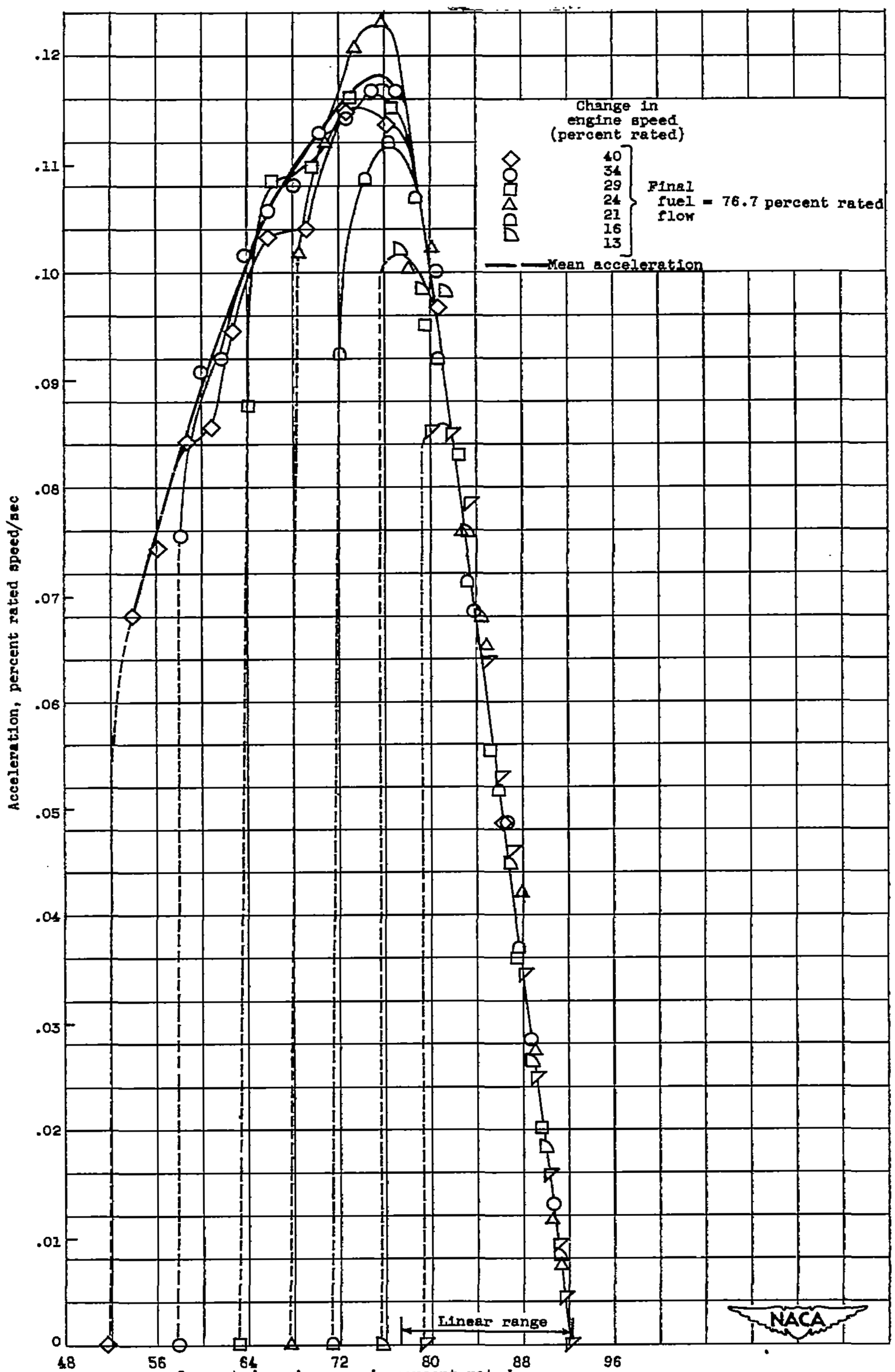

Figure 5. - Variation of acceleration from several initial engine speeds to set final engine speed from fuel-flow steps. Accelerations to 92 percent rated speed.

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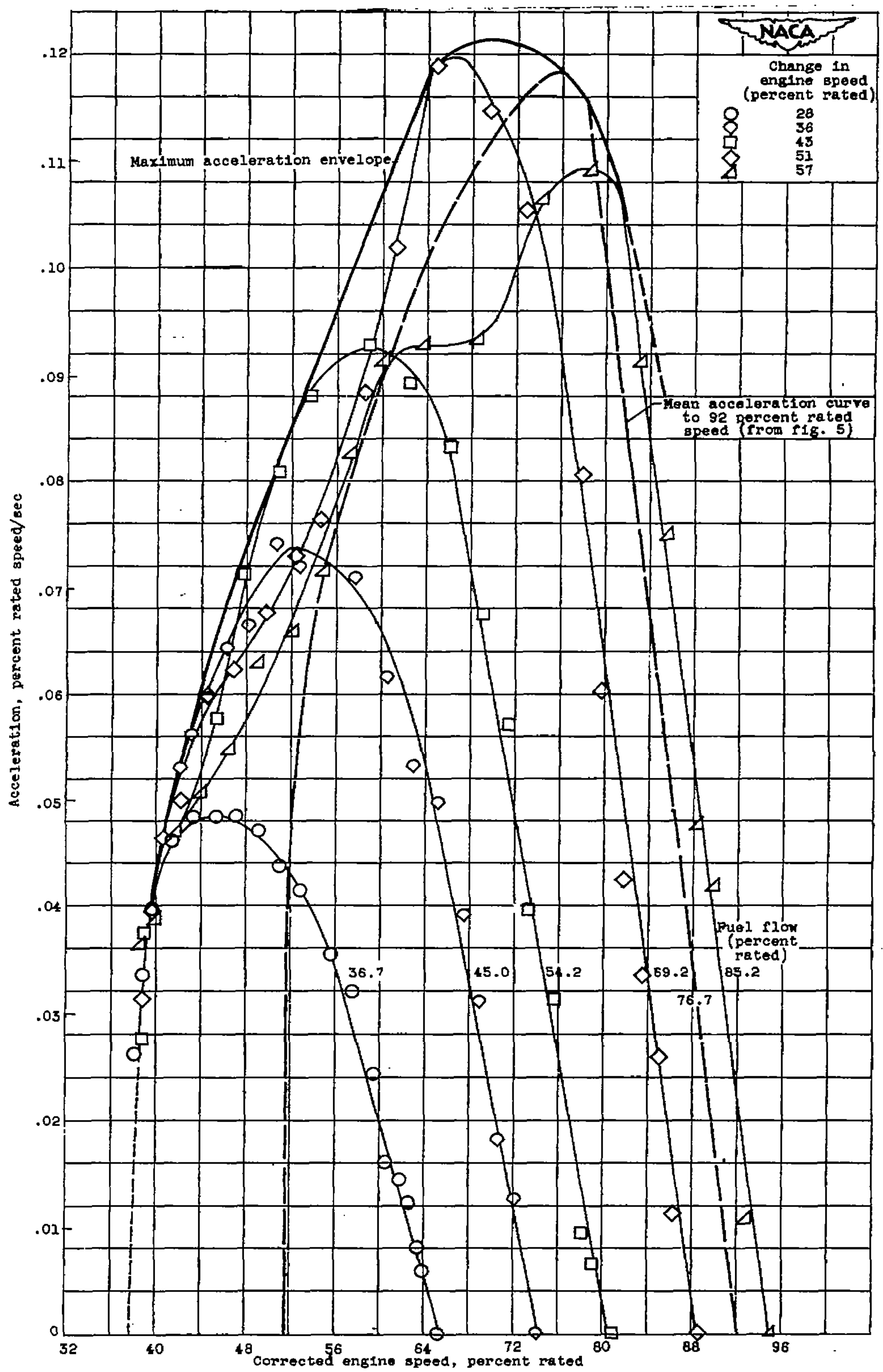

Figure 6. - Variation of acceleration from idle speed to several final speeds from fuel-flow steps.

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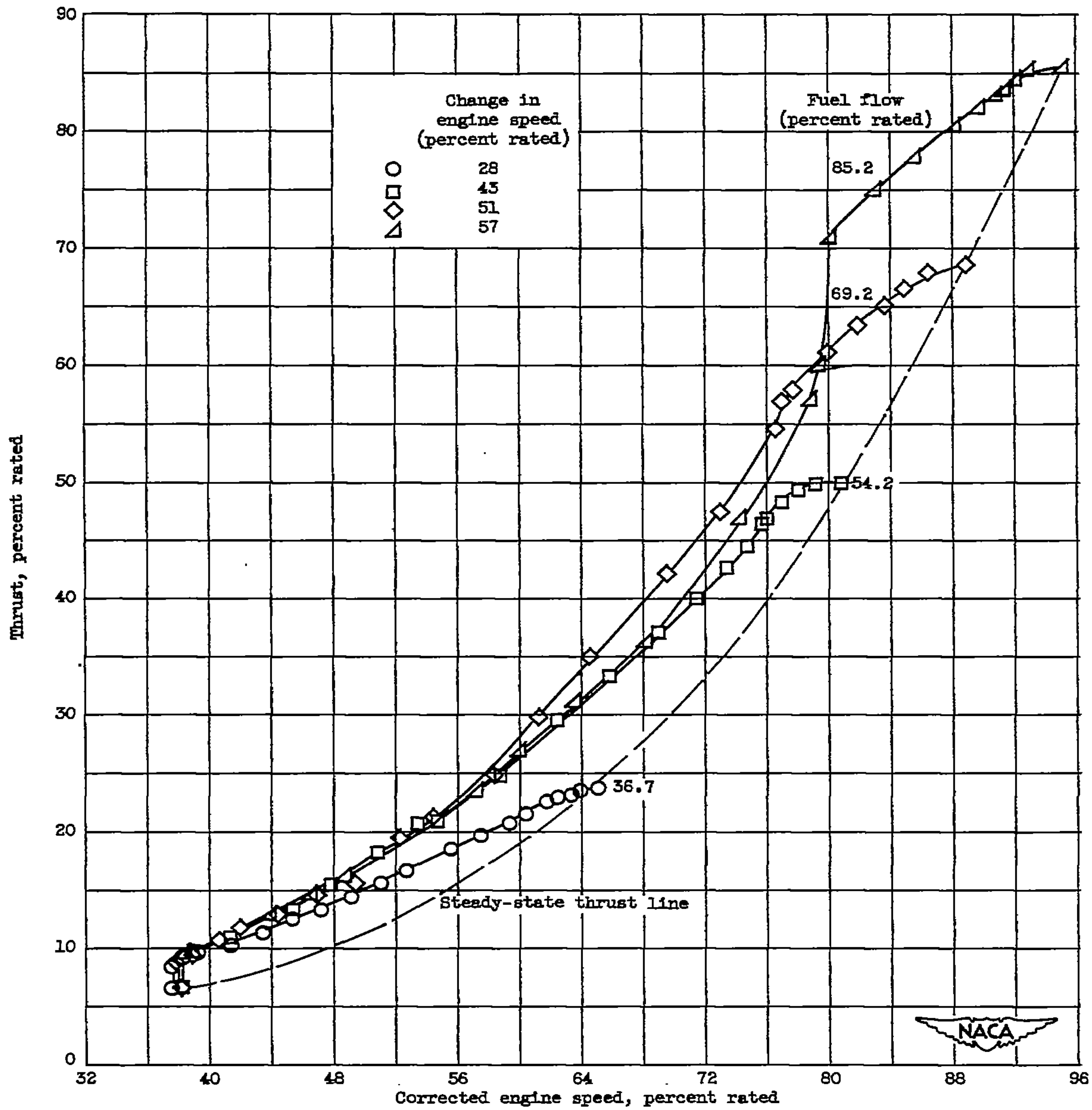

Figure 7. - Variation of thrust with speed for steps in fuel flow initiated at idle speed.

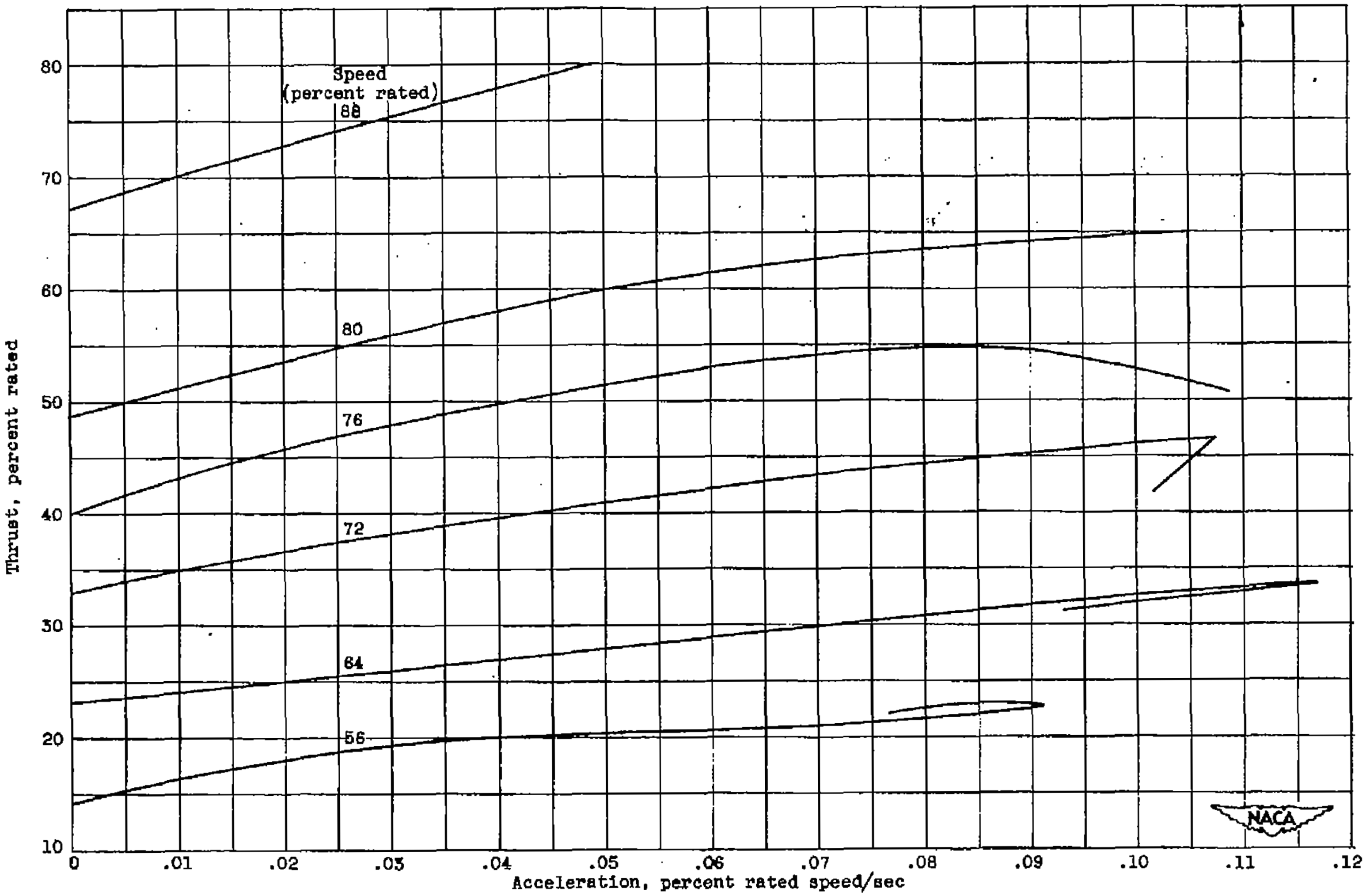

Figure 8. - Variation of thrust with acceleration from several steps in fuel flow initiated at idle speed (cross plot of figs. 7 and 8).

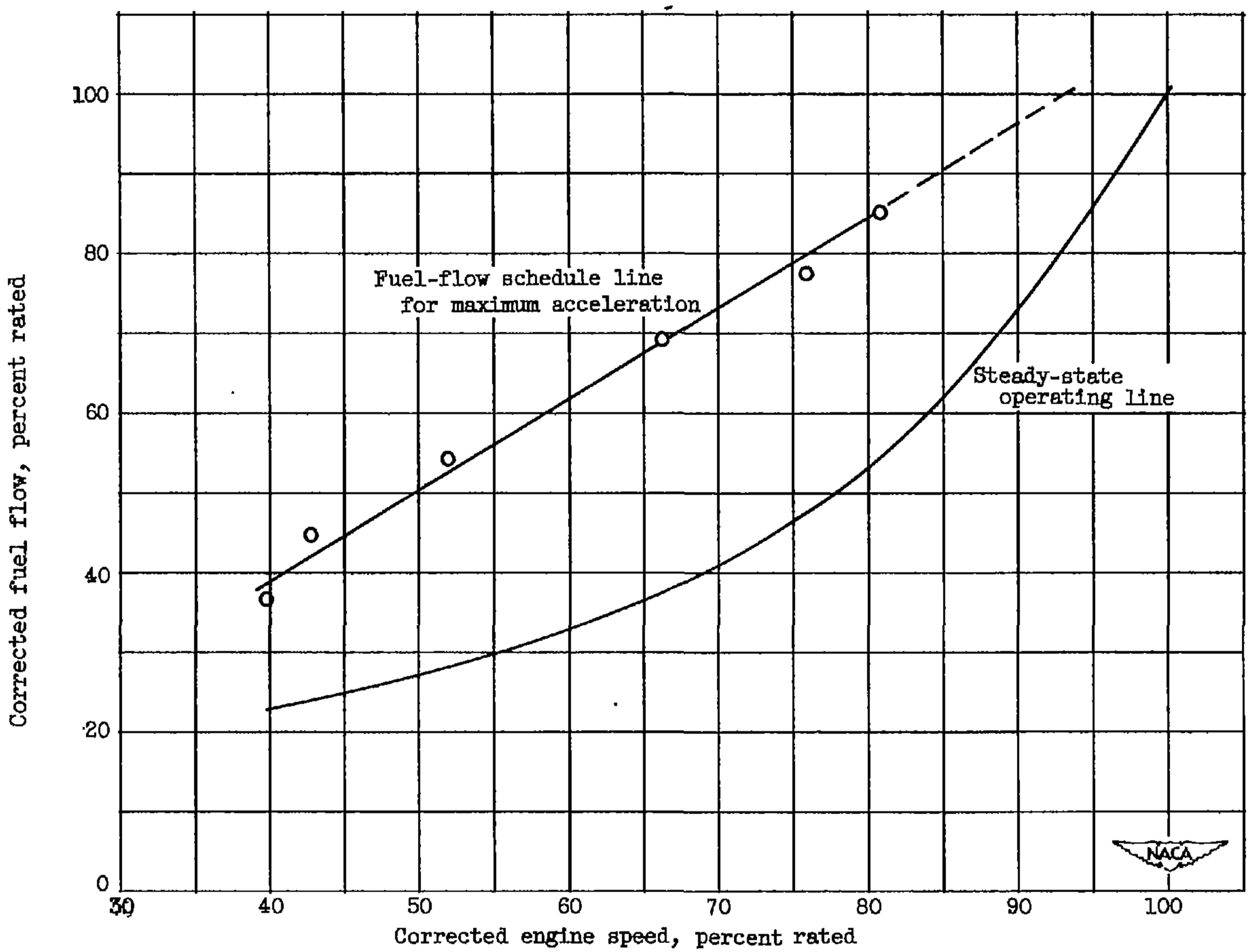

Figure 9. - Fuel-flow schedule for maximum acceleration.

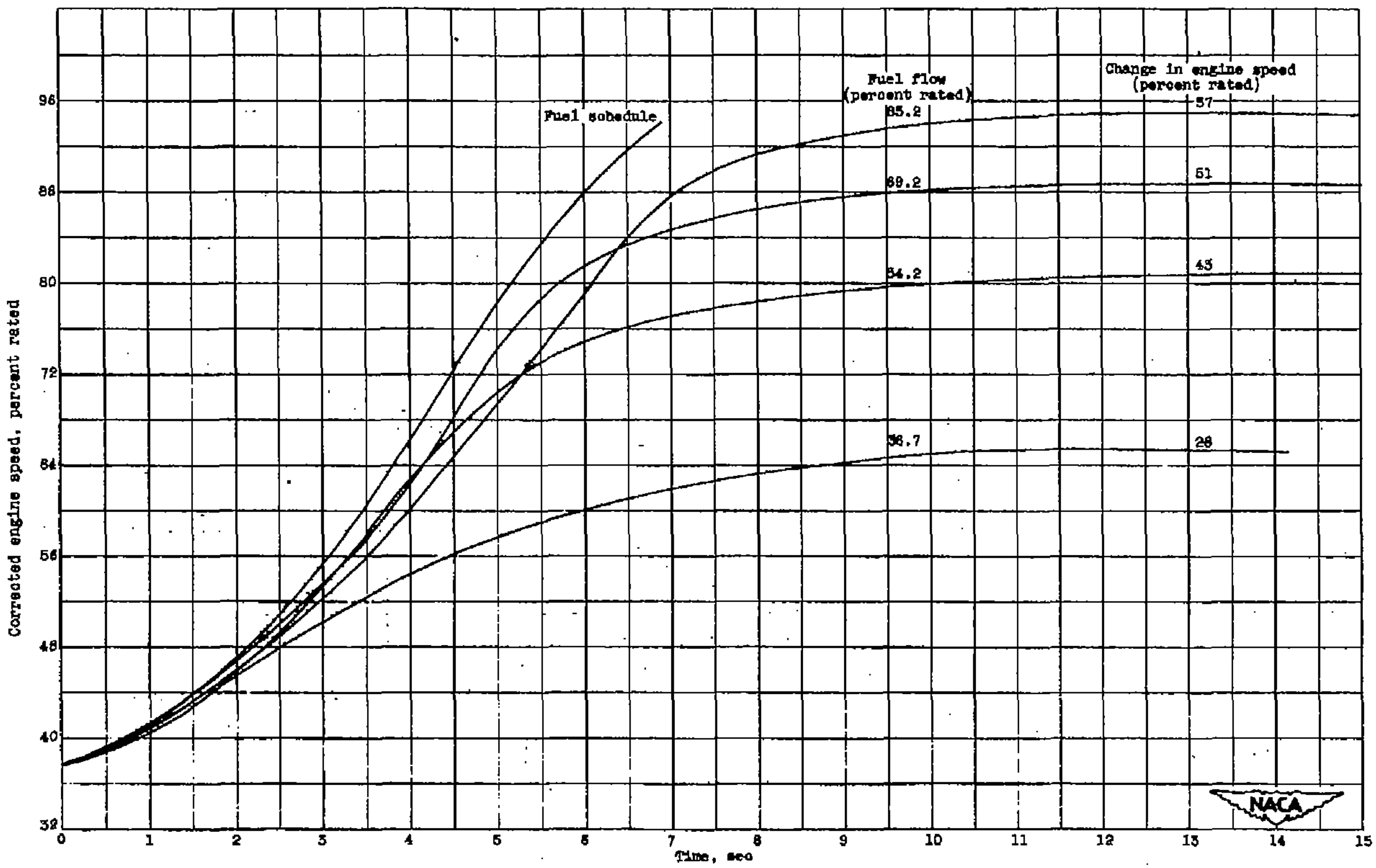

Figure 10. - Variation of engine speed with time for fuel-flow steps and scheduled fuel flow.

SECURITY INFORMATION

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